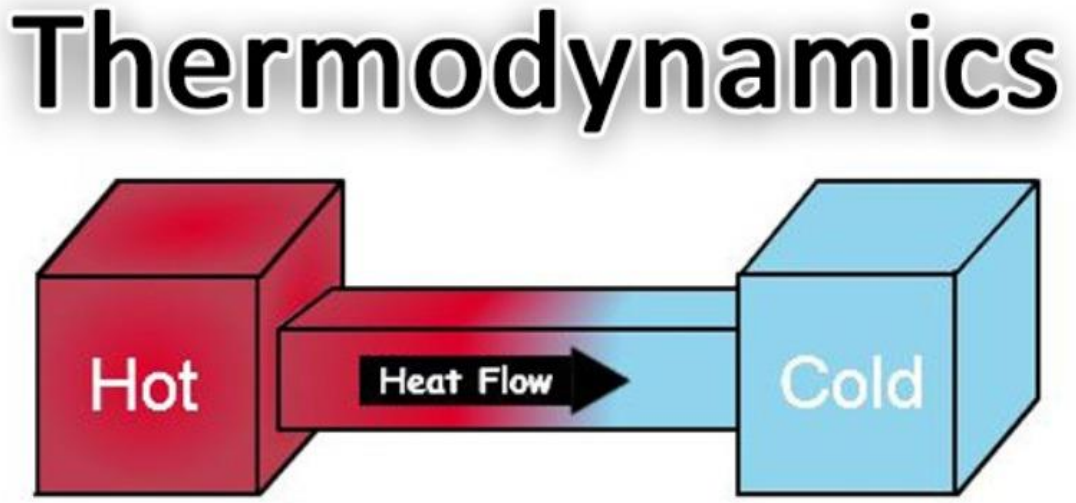
DEPARTMENT OF MECHANICAL ENGINEERING

ABIT

ENGINEERING THERMODYNAMICS



Module- V

Reciprocating Air Compressors

AIR COMPRESSORS

Air compressors are used to compress the air and to raise its pressure. It sucks the air to the cylinder from atmosphere, compresses it and then delivers the same under a high pressure.

Applications of air compressors

1. It is used to inflate the automobile tyres.
2. It is used to inject fuel in air injection diesel engines.
3. It is used foe spray painting.
4. It is used to operate pneumatic circuits.(such as pneumatic drills, hammers, hoist, air brakes,etc)
5. It is used to start IC engine and for supercharging IC engines.
6. It is used for gas turbine plants.
7. It is used for cleaning purposes.
8. It is used in the processing of food and firm maintenance.

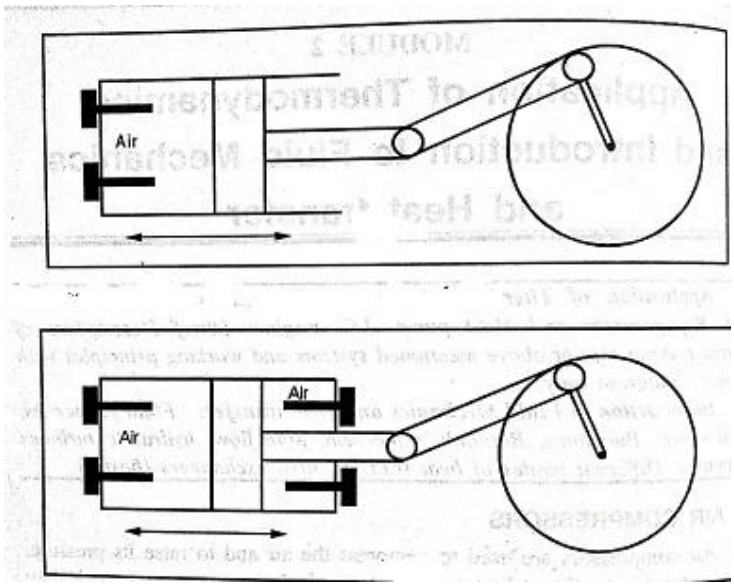
RECIPROCATING AIR COMPRESSORS

1. Single acting air compressor

In single acting air compressor, only one side of the piston is used to suck the air. Here both the suction and the compression takes place on the one side of the cylinder.

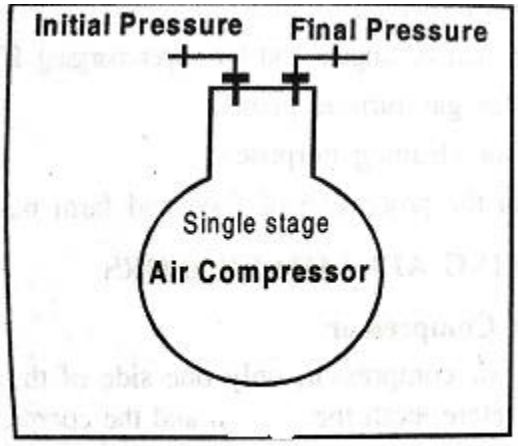
2. Double acting air compressor

In this compressor , both sides of the piston are used to suck the air. When suction is occurs in one side, compression and delivery will be taken on the other side. So simultaneously, two cycles will be completed in one revolution of the crank.



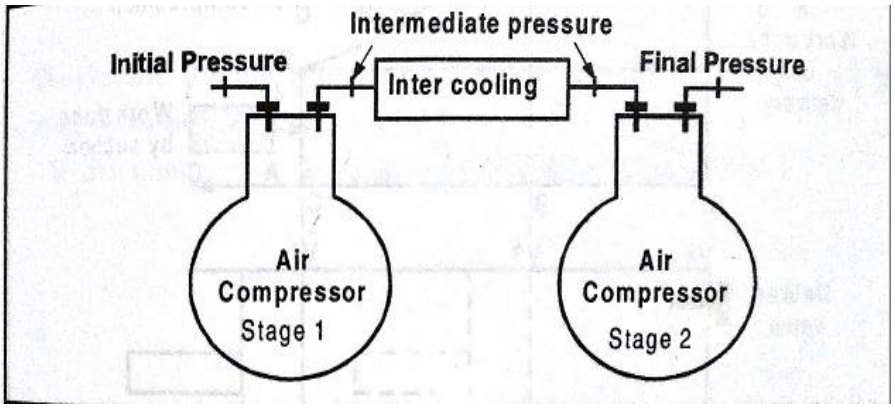
3. Single stage compressor

The compression of air from initial pressure to final pressure is carried out in one cylinder.

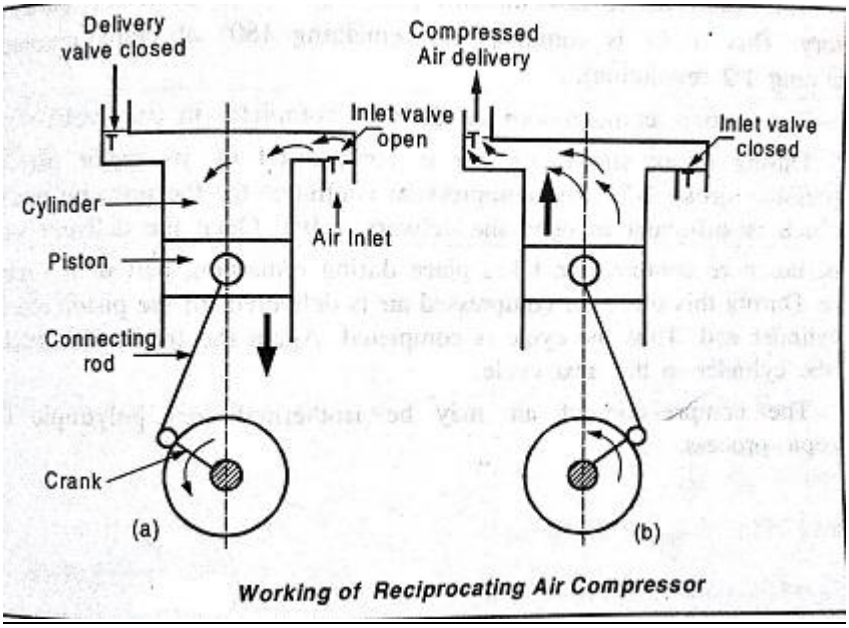


4. Multi stage compressor

The compression of initial pressure to final pressure is carried out in more than one cylinder.



Working principle of reciprocating air compressors

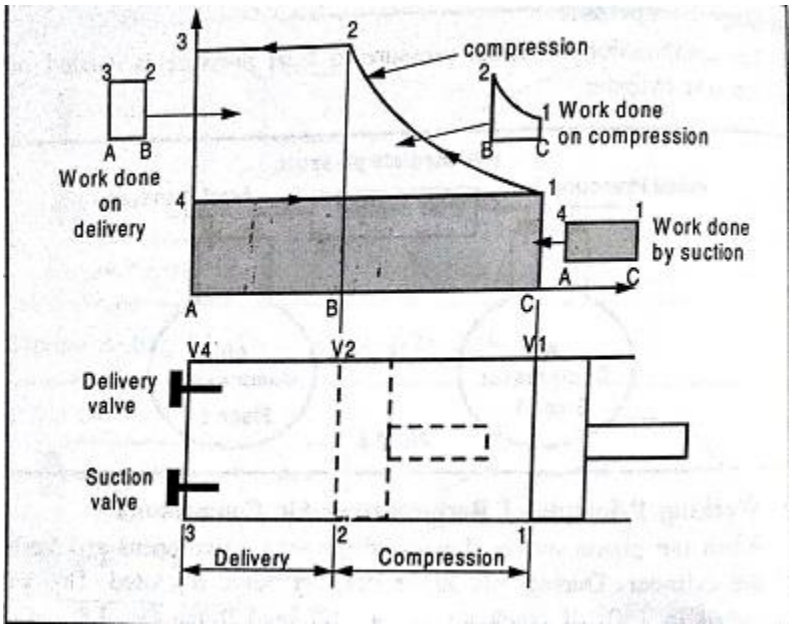


When the piston moves downward the inlet valve opens and fresh air enters the cylinder. During this stroke delivery valve is closed. This stroke is completed in 180^0 of crank revolution(1/2 revolution).

During the return stroke, the piston moves upward. Both valves are closed , so the compression of ir takes place . When the air is compressed to required pressure, the delivery valve opens. So the compressed air is delivered through delivery valve.

The return stroke is completed partly by compression and partly by delivery. This stroke is completed in remaining 180^0 of crank revolution (remaining ½ revolution).

The suction, compression and delivery completes in one cycle.

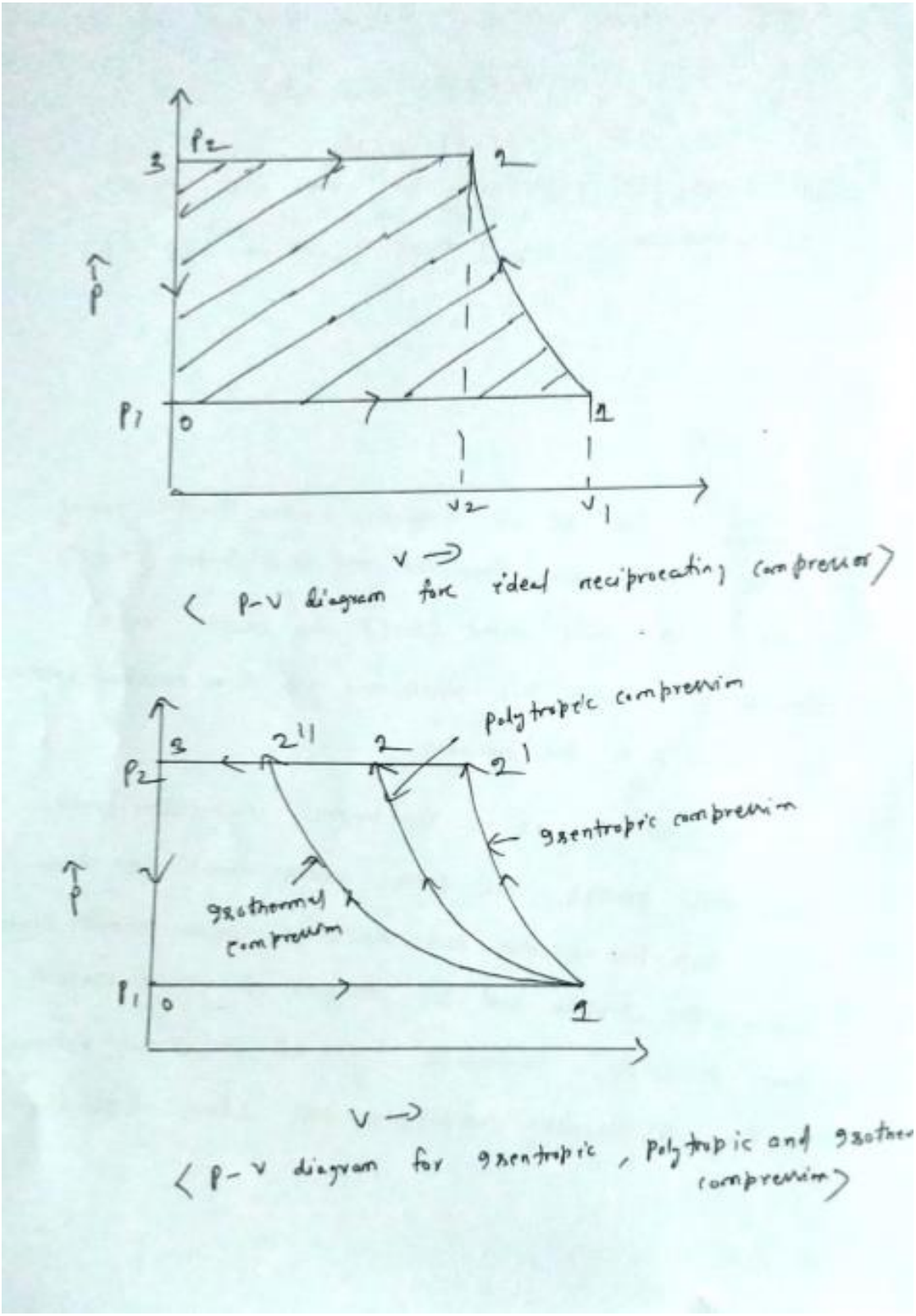


During return stroke , the air is compressedby its major part (i.e. compression stroke 1-2). The compression continues till the pressure reaches P_2 which is sufficient to open the delivery valve. Once the delivery valve opens, no more compression takes place during remaining part of the return stroke. During this time, the compressed air is delivered till the piston reaches the cylinder end. Thus the cycle is completed. Again the fresh air is sucked into the cylinder in the next cycle.

Q11 Derive the expression for work done by air compression. [BPUT 2nd sem 2018-19]

Process 0-1 :- This is an isobaric suction process, during which the piston moves from the top dead centre (TDC) to the bottom dead centre (BDC). The suction valve remains open during this process and gas at a constant pressure P_1 flows in to the cylinder.

Process 1-2 :- This is an isentropic compression process. During this process, the piston moves from BDC towards TDC. Both the suction and discharge valves remain closed during the process and the pressure of gas increases from P_1 to P_2. Various types of compression process in the reciprocating compressors are shown in the figure b



< P-V diagram for ideal reciprocating compressor >

< P-V diagram for isentropic, polytropic and isothermal compression >

Process 2-3 :- This is an isobaric discharge process. During this process, the suction valve remains closed and the discharge valve opens. Gas at a constant P_2 is expelled from the compressor as the piston moves to TDC.

Polytropic Compression

Area 0-1-2-3 in figure-(a) represents the net work done when the compression follows the polytropic law.

Net work on air per cycle = Area 0-1-2-3

= Work done during compression (1-2) + Work done during air delivery (2-3) — Work done during suction (0-1)

$$= \frac{P_2V_2 - P_1V_1}{n-1} + P_2V_2 - P_1V_1 = \frac{n}{n-1}(P_2V_2 - P_1V_1)$$

$$= \frac{n}{n-1} P_1V_1\left(\frac{T_2}{T_1} - 1\right) = \frac{n}{n-1} P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$W = \frac{nm}{n-1} RT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

Similarly, for isentropic compression

$$W = \frac{\gamma m}{\gamma - 1} RT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

Isothermal Compression

$$W = \text{area } 0-1-2''-3$$

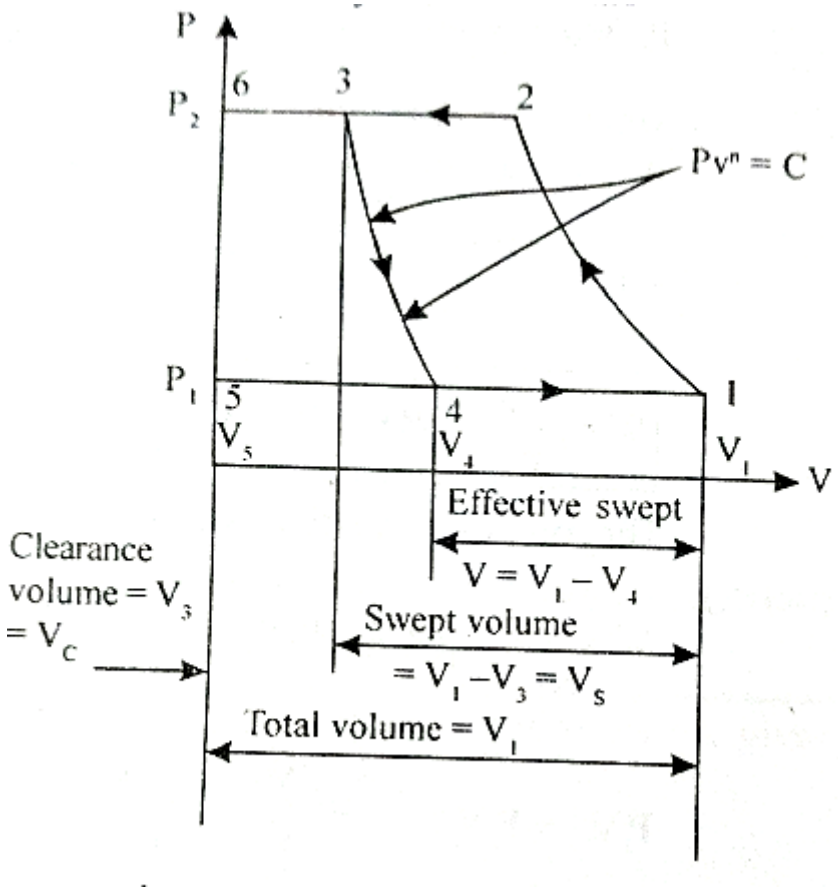
$$= P_2V_2'' + P_1V_1 \log_e \frac{V_1}{V_2''} - P_1V_1$$

$$\langle P_2V_2'' = P_1V_1 \rangle$$

$$\Rightarrow W = P_1V_1 \log_e \frac{V_1}{V_2''} = P_1V_1 \log_e \frac{P_2''}{P_1}$$

* In isothermal compression work done is minimum and it is maximum for adiabatic compression.

Equation for work (with clearance volume)



- The clearance volume is that volume which remains in the cylinder after the piston has reached the end of its inward stroke.
- The P-V diagram given shows at point '1' , the cylinder is full of intake air, volume 'V_1' and the piston is about to commence its compression stroke.
- The delivery pressure is 'P_2' and volume V_2.
- At 2 the delivery valve theoretically opens and for the remainder of the stroke 2 to 3 compressed air is delivered from the cylinder.
- At 3 the piston has reached the end of its inward stroke and so on, delivery of compressed air releases at 3.
- V_3 is the clearance volume and is filled at this stage with compressed air.

- As the piston begins the intake stroke this residual air will expand, according to the law $PV^n=C$ andit is not until the pressure has reduced to intake pressure at 4 that the inlet valve will begin to open thus permitting the intake of a fresh charge of air.
- For the remainder of the intake stroke a fresh charge is taken into the cylinder.
- Work done/cycle=Area 12341

  =Area 51265-Area 54365

$$\Rightarrow w=\frac{n}{n-1}P_1V_1\left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}-1\right\}-\frac{n}{n-1}P_4V_4\left\{\left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}}-1\right\}$$

$$But, P_4=P_1 and P_3=P_2 So$$

$$w=\frac{n}{n-1}P_1V_1\left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}-1\right\}-\frac{n}{n-1}P_1V_4\left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}-1\right\}$$

$$\Rightarrow w=\frac{n}{n-1}P_1(V_1-V_4)\left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}-1\right\}$$

Volumetric Efficiency

- The volumetric efficiency of a compressor is the ratio of free air delivered to the displacement of the compressor. It is also the ratio of effective swept volume to the swept volume.

$$Volumetric efficiency = \frac{Effective swept volume}{swept volume} = \frac{V_1 - V_4}{V_1 - V_3}$$

$$The ratio, \frac{clearance volume}{swept volume} = \frac{V_3}{V_1 - V_3} = \frac{V_C}{V_S} = K$$

$$\eta_{Vol} = \frac{V_1 - V_4}{V_1 - V_3} = \frac{(V_1 - V_3) + (V_3 - V_4)}{(V_1 - V_3)} = 1 + \frac{V_3}{V_1 - V_3} - \frac{V_4}{V_1 - V_3}$$

$$= 1 + \frac{V_3}{V_1 - V_3} - \frac{V_4}{V_1 - V_3}.\frac{V_3}{V_3} = 1 + \frac{V_3}{V_1 - V_3} - \frac{V_3}{V_1 - V_3}.\frac{V_4}{V_3} = 1 + k - k.\frac{V_4}{V_3}$$

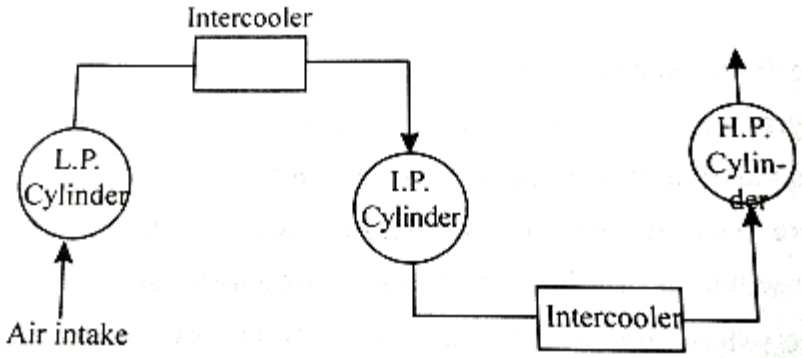
$$= 1 + k - k\left(\frac{P_3}{P_4}\right)^{\frac{1}{n}}$$

$$P_3 V_3^{\,n} = P_4 V_4^{\,n} \Rightarrow \frac{V_4}{V_3} = \left(\frac{P_3}{P_4}\right)^{\frac{1}{n}}$$

$$\eta_{Vol} = 1 + k - k\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} \left[\because P_3 = P_2, P_4 = P_1\right]$$

$$\Rightarrow \eta_{Vol} = 1 + k - k\left(\frac{V_1}{V_2}\right)$$

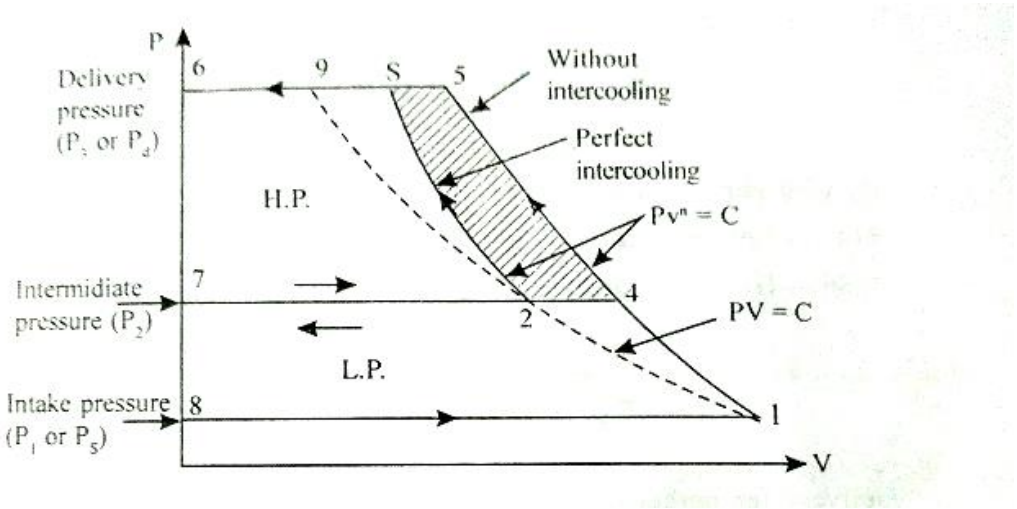
Multi-stage reciprocating compressor



(3-stage compressor)

- Multistage compression is a series arrangement of cylinders in which compresed air from the cylinder before, becomes the intake air for the cylinder which follows.
- The effective swept volume of this cylinder increases when pressure ratio is low in low pressure cylinder. Since in this cylinder which controls the mass flow through the machine .

- Because it is this cylinder which introduces the air into the machine, then there is a grater mass flow through the multistage arrangement than the single stage machine.
- In an intercooler the compressed air is cooled between cylinders, then the final delivery temperature is reduced.
- The reduction of temperature means the reduction in internal energy of the delivered air and this energy is used to drive the machine, this results in a decrease in input work requirement for a given mass of delivered air.



- From the above diagram the overall pressure range is P_1 to P_3.
- Cycle 8156 is that of single stage compressor. Cycle 8147 and 7456 are that of a two stage compressor without intercooling between cylinders.

Note: Perfect intercooling means that after the initial compression in the L.P. cylinder, with its consequent temperature rise, the air is cooled in an intercooler back to its original temperature.

CASE-I Single stage compressor

- As cycle 8156 is that of a single stage compressor, neglecting clearance, for this cycle

$$w = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_5}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

Deliverytemperature

$$T_5 = T_1 \left(\frac{P_5}{P_1} \right)^{\frac{n-1}{n}}$$

CASE-II: Two stage compressor

(Without intercooling)

8147-low pressure cycle

7456-high pressure cycle

So work done

$$w=\frac{n}{n-1}P_1V_1\left[\left(\frac{P_4}{P_1}\right)^{\frac{n-1}{n}}-1\right]+\frac{n}{n-1}P_4V_4\left[\left(\frac{P_5}{P_4}\right)^{\frac{n-1}{n}}-1\right]$$

(With perfect intercooling)

8147-low pressure cycle

7236-high pressure cycle

$$w=\frac{n}{n-1}P_1V_1\left[\left(\frac{P_4}{P_1}\right)^{\frac{n-1}{n}}-1\right]+\frac{n}{n-1}P_2V_2\left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}}-1\right]$$

$Delverytemperature$

$$T_3=T_2\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}}=T_1\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}}\left(\because T_1=T_2\right)$$

$$So, P_2V_2=P_1V_1(\because T_1=T_2)$$

$$P_4=P_2$$

$$w=\frac{n}{n-1}P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}+\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}}-2\right]$$

Condition for minimum work

$$For\ \min imum work, \frac{dW}{dP_2} = 0$$

$$\Rightarrow \frac{d\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}}\right]}{dP_2} = 0 \Rightarrow \frac{1}{(P_1)^{\frac{n-1}{n}}} x\left(\frac{n-1}{n}\right) P_2^{\left(\frac{n-1}{n}\right)-1} + (P_3)^{\frac{n-1}{n}} x - \left(\frac{n-1}{n}\right) P_2^{-\left(\frac{n-1}{n}\right)-1} = 0$$

$$\Rightarrow \frac{1}{(P_1)^{\frac{n-1}{n}}} x \frac{n-1}{n} (P_2)^{\frac{-1}{n}} = (P_3)^{\frac{n-1}{n}} x\left(\frac{n-1}{n}\right) P_2^{\frac{-2n+1}{n}} \Rightarrow \frac{P_2^{\frac{-1}{n}}}{P_2^{\left(\frac{-2n+1}{n}\right)}} = (P_1 P_3)^{\frac{n-1}{n}}$$

$$\Rightarrow P_2^{\left(\frac{2n-2}{n}\right)} = (P_1 P_3)^{\frac{n-1}{n}} \Rightarrow P_2^{\ 2} = P_1 P_3$$

$$\Rightarrow P_2 = \sqrt{P_1 P_3}$$

$$\Rightarrow \frac{P_2}{P_1} = \frac{P_3}{P_2}$$

Hence ratio per stage is equal P_2 will ideal intermediate pressure with perfect intercooling , will give the minimum w.

$$Hence, w = \frac{2n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] = \frac{2n}{n-1} P_1 V_1 \left[\left\{\frac{(P_1 P_3)^{1/2}}{P_1}\right\}^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{2n}{n-1} P_1 V_1 \left[\left(\frac{P_3}{P_1}\right)^{\frac{n-1}{2n}} - 1\right]$$

Note: P_3/P_1 is the pressure ratio through the compressor.

Case-III Multistage compressor

For single stage

$$w = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

For two stage compressor

$$w = \frac{2n}{n-1} P_1 V_1 \left[\left(\frac{P_3}{P_1} \right)^{\frac{n-1}{2n}} - 1 \right]$$

For a three stage compressor

$$w = \frac{3n}{n-1} P_1 V_1 \left[\left(\frac{P_4}{P_1} \right)^{\frac{n-1}{3n}} - 1 \right]$$

For x stage compressor

$$w = \frac{xn}{n-1} P_1 V_1 \left[\left(\frac{P_{(x+1)}}{P_1} \right)^{\frac{n-1}{xn}} - 1 \right]$$

Also , for an ideal compressor there is equal work per cylinder, for an x-stage compresso

$$w = \frac{xn}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

Intermediate pressure for x stage compressor

Pressure ratio per stage is equal

$$\frac{P_2}{P_1} = \frac{P_3}{P_2} = \frac{P_4}{P_3} \ldots\ldots\ldots\ldots \frac{P_{(x+1)}}{P_x} = z(say)$$

$$\therefore P_2 = zP_1$$

$$P_3 = zP_2 = z^2 P_1$$

$$P_{x+1} = zP_x = z^x P_1$$

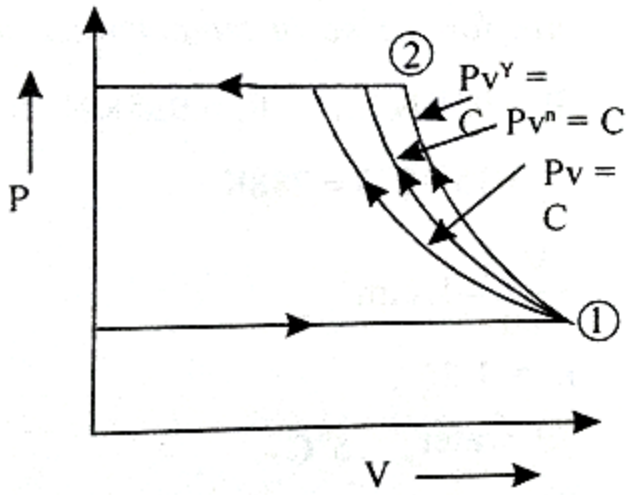
$$z^x = \frac{P_{x+1}}{P_1} \Rightarrow z = x\sqrt{\frac{P_{x+1}}{P_1}} = x\sqrt{\text{Pr}essureratiothroughcompressor}$$

Q. A single acting , single stage reciprocating air compressor , 250 mm bore and 350 mm stroke runs at 3 rps . The section and delivery pressure are 0.98 bar and 6 bar respectively. Calculate the theoretical power required to run it under each of the following condition of compressor.

(a) Isothermal (b) Polytropic, n= 1.25 (c) adiabatic, ϒ=1.4

Neglecting clearance, also calculate isothermal efficiency for (b) and (c).

Solution:



D= 250 mm=0.25 m

L= 350 mm =0.35 m

r.p.s =3

P_1=0.98 bar=98 KN/m^2

P_2=6 bar =600 KN/m^2

Cylinder volume = $V_1 = \frac{\pi}{4} D^2 LN = \frac{\pi}{4}(0.25)^2 X\, 0.35 X\, 3 = 0.05151 m^3/s$

(a) Isothermal compression

$$w = P_1 V_1 \ln\left(\frac{P_2}{P_1}\right) = 98 X\, 0.05151 \ln\left(\frac{600}{98}\right) = 9.146 KW$$

(b) Polytropic compression

$$w = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] = \frac{1.25}{1.25-1} X\, 98 X\, 0.05151 \left[\left(\frac{600}{98}\right)^{\frac{1.25-1}{1.25}} - 1\right] = 11.023 KW$$

© Adiabatic compression

$$w=\frac{\gamma}{\gamma-1}P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}-1\right]=\frac{1.4}{1.4-1}X\,98X\,0.05151\left[\left(\frac{600}{98}\right)^{\frac{1.4-1}{1.4}}-1\right]=11.981KW$$

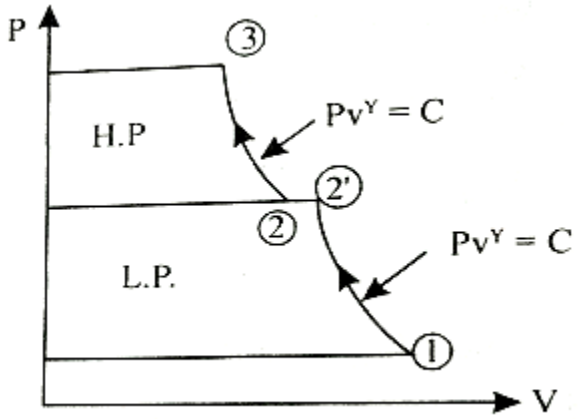
Isothermal efficiency

$$\frac{w_{iso}}{w_{poly}}=\frac{9.146}{11.023}=82.97\%$$

$$\frac{w_{iso}}{w_{adia}}=\frac{9.146}{11.981}=76.33\%$$

Q. In two stage air compressor the L.P cylinder draws in 0.3 m^3/min at a temperature of 20^0C and a pressure of 100 KN/m^2. It is compressed adiabatically to 3 bar and then delivered to a receiver , where the air is cooled under constant pressure to 20^0C. This air is drawn into the H.P cylinder and compressed adiabatically to 9 bar and deliver to the reservoir. Considering the compressor single acting calculate the power required to run at 120 rpm. Neglect clearance.

Solution:



V_1=0.3 m^3/min

T_1=T_2=20^0C

P_1=100 KN/m^2

P_2=300 KN/m^2

P_3=900 KN/m^2

Rpm=120

The intermediate pressure given is = the minimum pressure required for perfect intercooling

$$P_2 = \sqrt{P_1 X P_3} = \sqrt{100 X 900} = 300 KN/m^2$$

$$w/\min = \frac{2n}{n-1} P_1 V_1 \left[\left(\frac{P_3}{P_1} \right)^{\frac{n-1}{2n}} - 1 \right] = \frac{2X1.4}{1.4-1} X100X0.3 \left[\left(\frac{900}{100} \right)^{\frac{1.4-1}{2(1.4)}} - 1 \right] = 210KJ$$

$$Power = 210/60 = 3.5KW$$

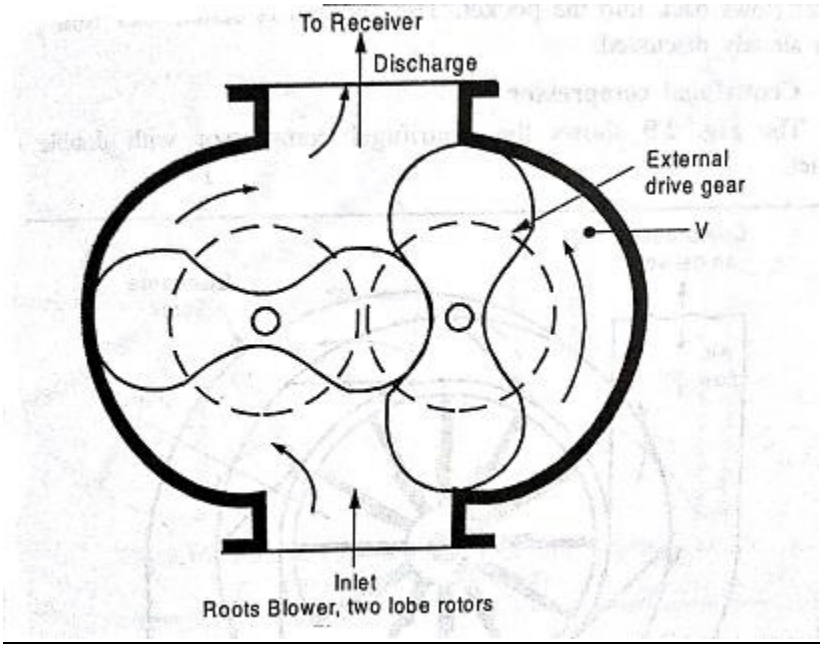
ROTARY COMPRESSORS

Rotary compressors are used to compress large quantity of air at a relatively low pressure . In rotary air compressor , the air is trapped in between two sets of engaging surfaces (lobes) and the pressure of air is increased by squeezing action or back flow of air.

Different types of rotary compressors

1. Roots blower compressor
2. Vane type blower compressor
3. Centrifugal compressor
4. Axial flow compressor

Roots Blower



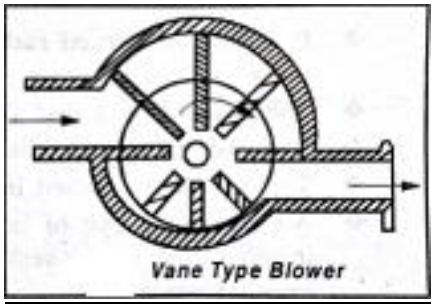
Roots Blower, two lobe rotors

Roots blower compressor consists of two rotors with lobes . These lobes are rotating in air tight casing. It has inlet and outlet port. The shape of the lobes is epicycloid or hypocycloid or involute. During the rotation , volume of air at atmospheric pressure is trapped between left hand lobe and casing. The further rotary motion of the lobes delivers the entrapped air into the receiver. So more and more flow of air into the receiver increases its pressure.

Back flow of Air

When the rotating lobe uncovers the exit port, the high pressure from receiver flows back into the casing. The high pressure air and trapped air gets mixed . The back flow process continues till the trapped air and receiver air attains the equal pressure. Then the pressure of air trapped in the pocket (in between lobe and casing) is increased at constant volume entirely by back flow of air. Finally , the high pressure air from receiver is delivered to the requirement.

Vane type Blower Compressor

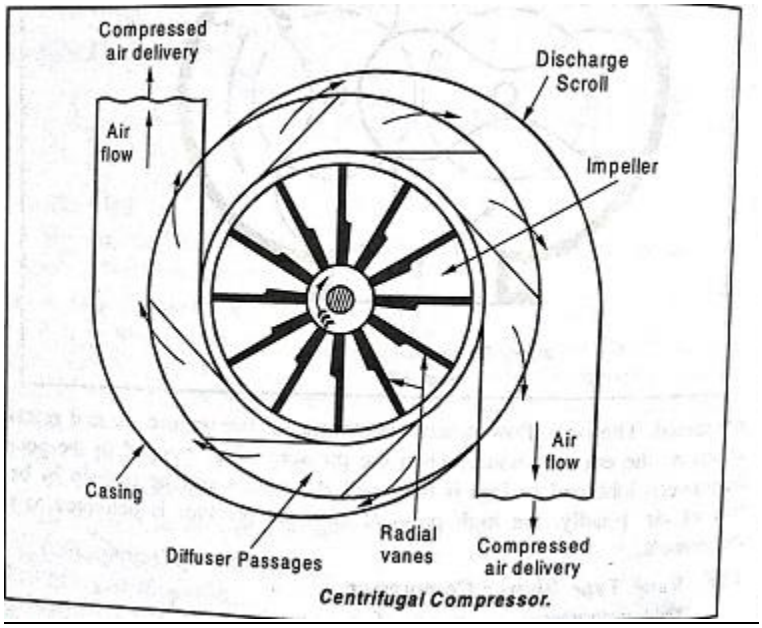


This compressor comprises of a disk rotating eccentrically in an air tight casing. It has inlet and outlet port. The disc has many number of vanes. When the rotor rotates , the air is trapped in the pockets formed between the vanes and casing.

The compression is occurred due to decreasing volume and back flow of air.

First of all , the rotary motion of the vanes compresses the air. Next when the rotating vane uncovers the exit port, the high pressure air from receiver flows back into the pocket. This process is called back flow process .

Centrifugal compressor



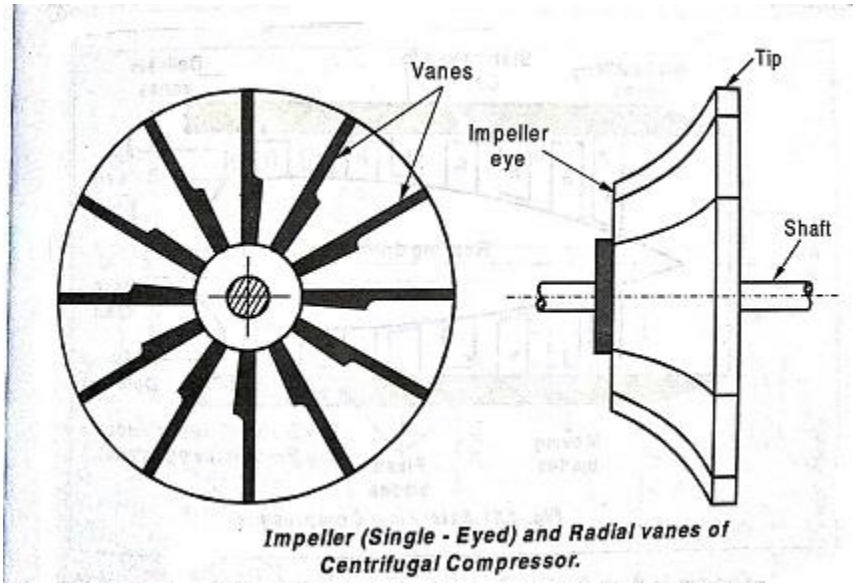
Centrifugal Compressor.

It consists of curved radial vanes which are attached to the shaft and rotate. The impeller is a disc fitted with radial vanes. The casing is surrounding the rotating impeller. The diffuser is housed in a radial portion of the housing.

Air enters the eye of impeller . Due to the centrifugal action of impeller, the air moves radially outwards with the guidance of impeller vanes. The impeller transfers energy to air by increasing its pressure rise.

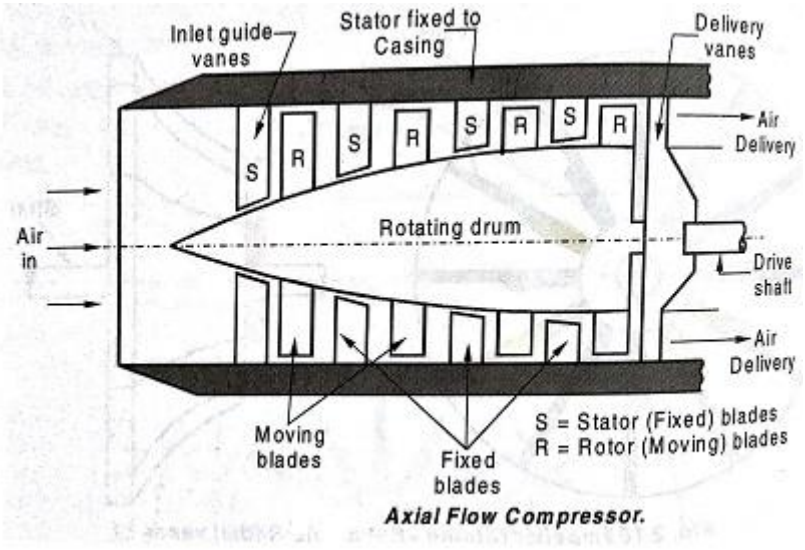
Then the air enters diverging portion called diffuser. Here , the kinetic energy is converted into pressure rise further. Nearly half the pressure rise is achieved by impeller and remaining by diffuser.

A pressure ratio of 5:1 is obtained by single stage centrifugal compressor and for higher pressure ratio multi stage compressors are used.



Impeller (Single - Eyed) and Radial vanes of Centrifugal Compressor.

Axial Flow Compressor



Axial Flow Compressor.

In this axial flow compressor , air is flowing parallel to the axis of compressor. It consists of stators(fixed blades) and rotars (rotating blades) in an alternate rows

The rotars are fixed with rotating drum and stators are fixed to the casing. One stage of compressor means one row of stator blades with one row of rotar blades.

The work energy of moving blades is transferred to air to accelerate. The blades are so arranged that the space between the blades forms diffuser passage and hence air pressure is increased at the expense of velocity.

The air is then further flows through stator blades and gets diffused and its pressure is further increased. After air gets pressure rise in one stage , it will be allowed to pass second stage and pressure is continuously raised.

The annular area is normally reduced from inlet to outlet of the compressor to keep the flow velocity constant.

The stator blades serve to convert a part of kinetic energy in to pressure energy and to guide air from one stage to next stage without shock.